Jet Propulsion Laboratory
California Institute of Technology

Energy-Aware Data Routing for Disruption Tolerant Networks in Planetary Cave Exploration

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Acknowledgments
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Outline

- Motivation
- Cave Exploration
- Proposed Study on Data Routing
- Experiments
- Conclusion and Future Work

Motivation

Mars caves:

- Potential human settlements [Boston et al. 2003]
- Understanding the evolution of the planet [Boston et al. 2005, 2004]
- The search for life
- > 2000 cave-related features

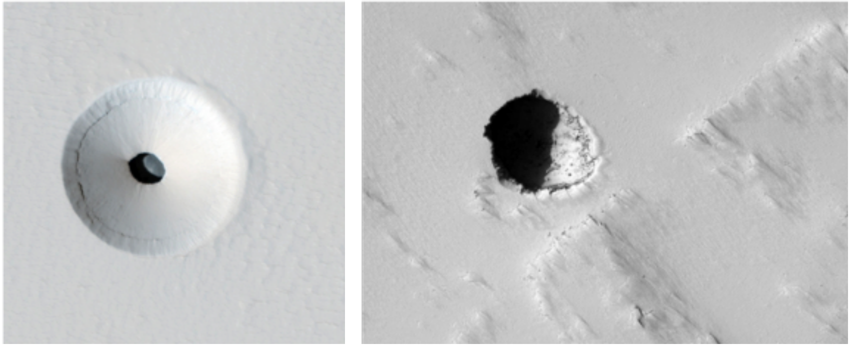


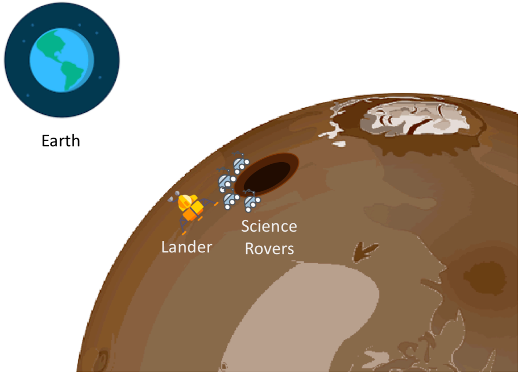
Image Credit: NASA/JPL/University of Arizona

Robotic Exploration - Challenges

- Unknown environment
- No sunlight: cannot recharge, limited lifetime, *power key resource*
- Communication with earth is limited: no humans in the loop, transfer data out to a base station

Multi-robot exploration is promising:

- Redundancy
- Network
- Coverage



Previous Work: Multi-Robot Cave Exploration

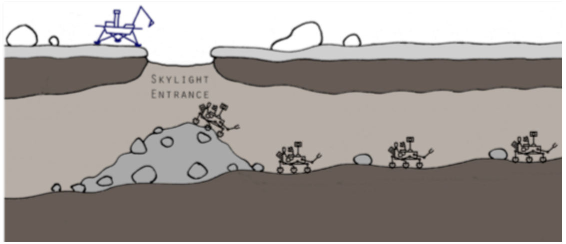
A multi-robot coordination problem

Dynamic Zonal Relay with Sneakernet Relay [Vaquero et al. 2018]

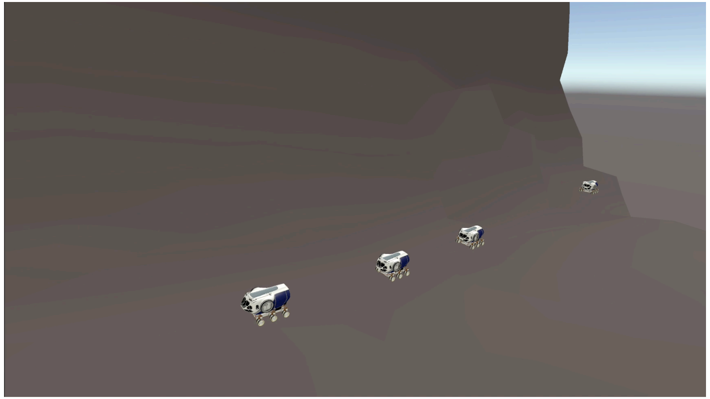
Coordinates rovers to expand zones deeper into the cave and relay data out

Dynamic Zonal — *Sneakernet*

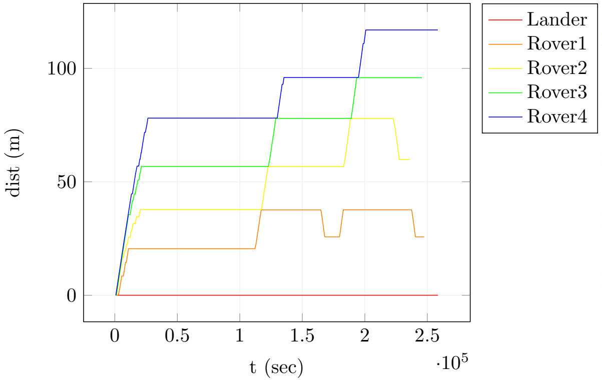
Leader	Drive to Zone	Characterize Zone	Transmit Science Data	Drive to New Zone	Characterize Zone	Drive to Relay	Transmit Science Data	Drive to New Zone	Characterize Zone
Relayer	Drive to Zone	Characterize Zone	Transmit Science Data	Drive to New Zone	Relay	Drive to Relay	Transmit Science Data	Drive to New Zone	Relay

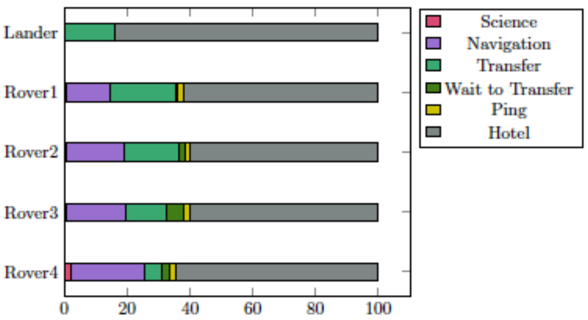


Artist concept. Rovers not to scale. Image Credit: Figure adapted from the Wikimedia Commons, Longitudinal cross-section of a Martian lava tube with skylight.



Credit: Rover 3D model, a notional Space Exploration Vehicle (SEV), from NASA LaRC Advanced Concepts Lab, AMA Studios.





Vaquero, T.; Troesch, M.; and Chien, S. 2018. An approach for autonomous multi-rover collaboration for mars cave exploration: Preliminary results. In International Symposium on Artificial Intelligence, Robotics, and Automation in Space (i-SAIRAS 2018) .

Study Objective

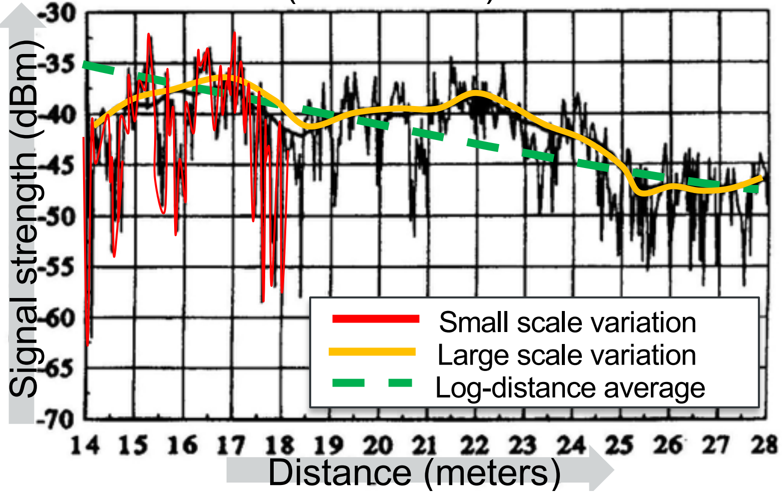
- Preliminary exploratory analysis on **decentralized energy-aware data routing protocols**
- Focusing on planetary cave exploration with multiple networked robots
- Want to analyze advantages and disadvantages with respect to:
  - Energy usage
  - Robot lifetime
  - Data delivery

Communication in Caves

Field testing of communication links

Walsh, W., and Gao, J. 2018. Communications in a cave environment. In Proceedings of the 2018 IEEE Aerospace Conference, 1–8. IEEE.

Example of Large and Small-Scale Fading (**NOTIONAL**)



Influenced by: Tx-Rx Distance, Obstacles, line-of-sight, antenna elevation, distance to walls

Can cause large *constructive* and *destructive* fading effects

Model:

$$SNR(d) = SNR_o - 10n\log_{10}(d/d_o) - X - Y$$

$$BW = \begin{cases} 0 & \text{if } 0 \leq SNR \leq 37 \\ 1 & \text{if } 37 < SNR \leq 40 \\ 2 & \text{if } 40 < SNR \leq 44 \\ 5.5 & \text{if } 44 < SNR \leq 47 \\ 11 & \text{if } SNR > 47 \end{cases}$$

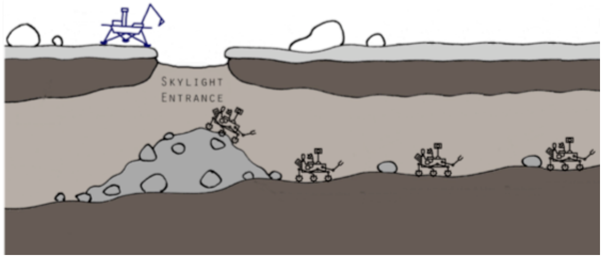
Communication in Caves

Promising Framework: **Delay/Disruptive Tolerant Network (DTN)**

- What is it?
  - Set of network protocols that enable communications in challenged environments (delays, disruptions, errors).
  - Originally developed for deep space communications (long propagation delays and episodic connectivity).
  - Operates in a hop-to-hop basis (store and forward) and minimizes hand-shaking procedures.
- Routing in DTNs:
  - Large body of research over the last 20 years, optimizing different metrics.
  - Multiple algorithms proposed. At their core, they vary in the degree of network state knowledge assumed for making routing decisions:
    - Controlled flooding techniques is on the lower end of that spectrum (suitable for abundant bandwidth and low network knowledge)
    - Prediction-based techniques using statistical analysis to infer probability of successful packet delivery.
    - Contact Graph Routing uses contact plan (knowledge provided a priori), data flow info is recorded to avoid overbooking
- Using DTN for space exploration in energy-constraint environment (e.g., planetary caves) has not been considered.

Proposed Study

- Based on our previous work, we assume the quasi-linear, swarm exploration with multiple robots:
  - Assigned sections of the cave to each robot to explore
  - Science data is generated at a certain frequency as they explore
- Data has to be sent to a static base station at the cave entrance
- Focus on selected data routing protocols
  - Opportunistic (with preferable path)
  - Schedule-based (DTN based)
- Run Simulation and analyze results



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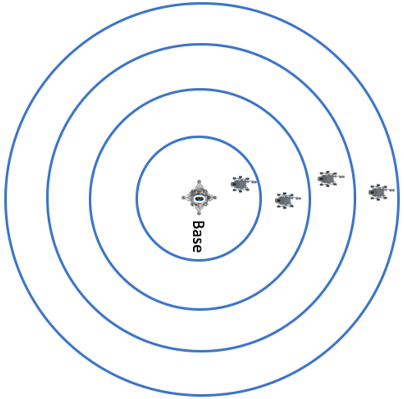


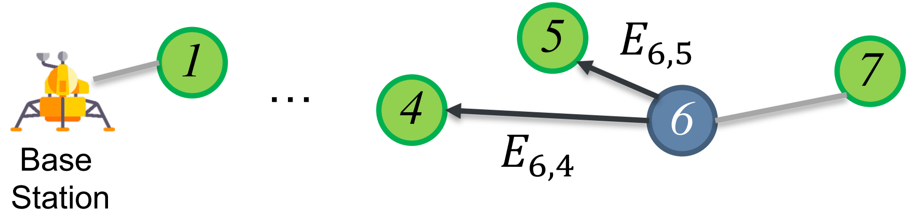
Investigated Data Routing Protocols

Opportunistic (with preferable path)

1) Energy Estimate

- Immediate neighbors ($i > j$)
- Lowest energy to transfer E_{ij}
- Closest to the cave entrance

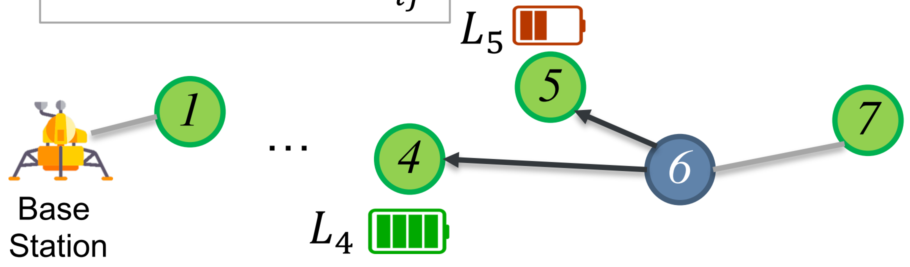
$$E_{ij} = (P_{txi} + P_{rxj})\frac{S}{BW_{ij}}$$



2) Energy Left

- Immediate neighbors ($i > j$)
- Greatest energy left after transfer L_j
- Closest to the cave entrance

$$L_j = B_j - P_{rxj}\frac{S}{BW_{ij}}$$

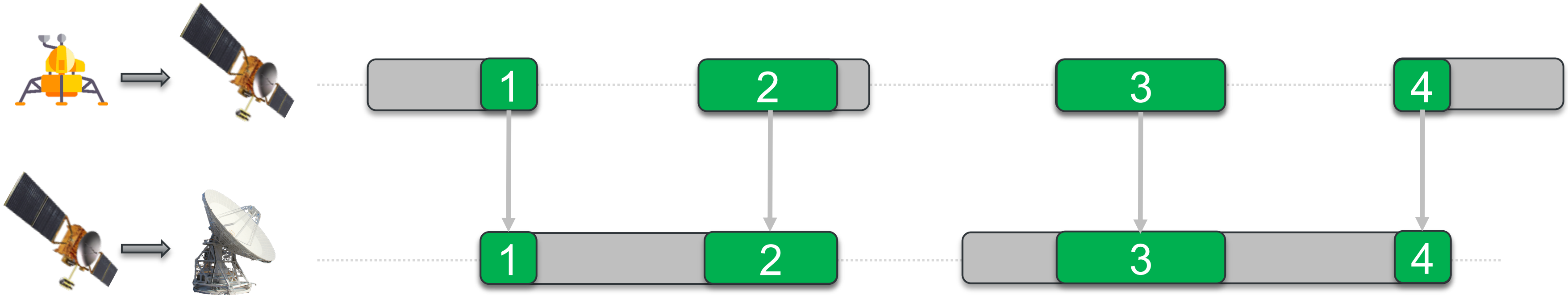


Investigated Data Routing Protocols

Schedule-based

3) Contact Graph Routing (CGR)

- Originally developed to route in fully predictable network.
- Requires each node to have a “contact plan” that indicates the contact opportunities between all nodes in the system.
- To route data, the contact plan is used to build a time-varying topology graph. Paths from origin to destination are then computed using dynamic programming.

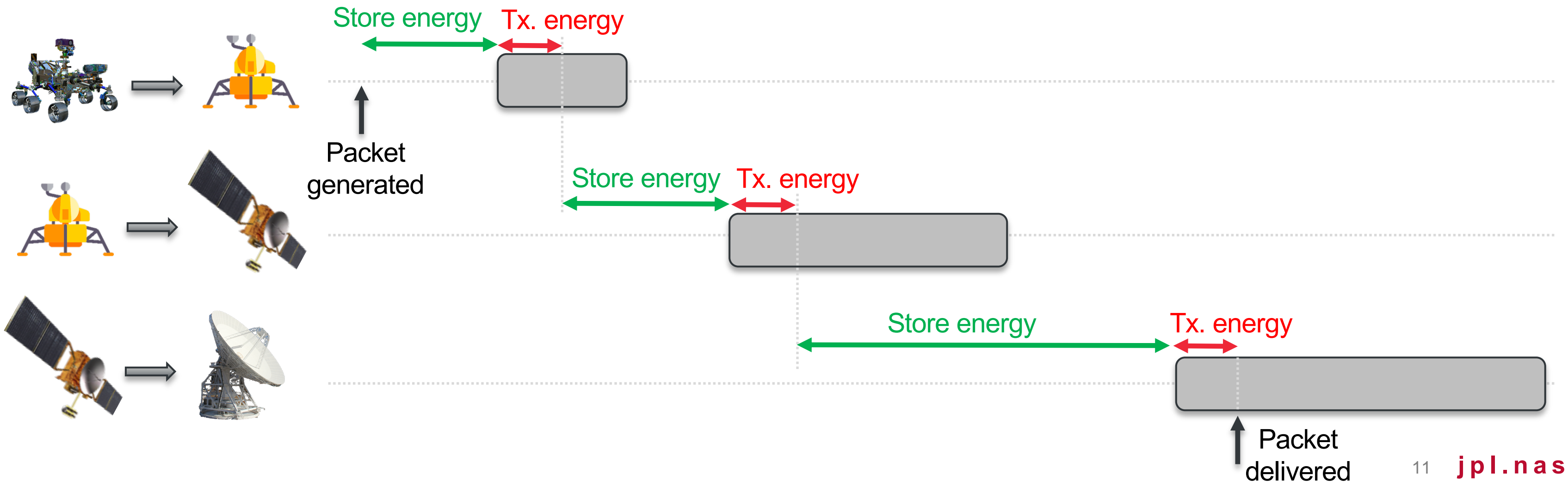


Investigated Data Routing Protocols

Schedule-based

4) Energy-Aware Contact Graph Routing (ECGR)

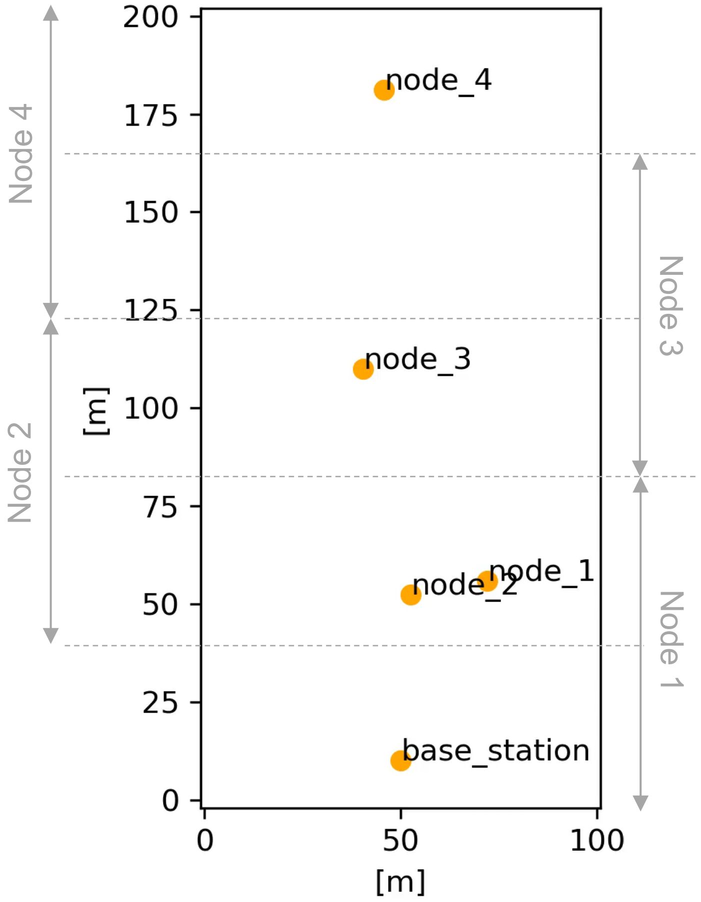
- Based on traditional CGR.
- Best path minimizes *least total energy* consumed by a given packet.
  - *Total energy:* Energy to store packet + energy to transmit packet to next node in path.
  - *Least*: Energy to store packet does not take into account energy consumed while waiting for other packets to be sent.



Experiments in Simulation

Setup – Cave Exploration Scenarios

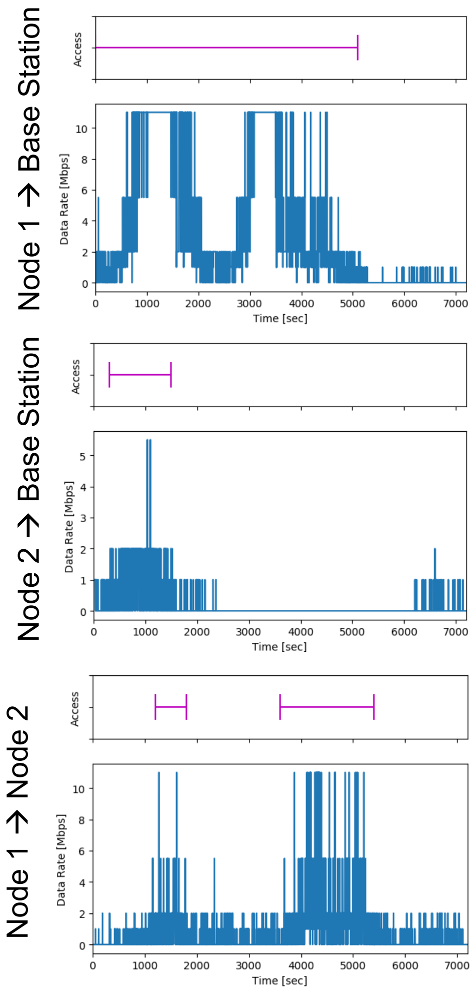
- Linear cave divided in overlapping sections.
- Robot motion precomputed using
  - Randomized way-point model.
  - Very low speed (0.05 m/s).
- Assumptions:
  - All robots have the same capabilities.
  - Initial robot battery charge is set.
  - Robots cannot recharge.
  - Battery decays.
  - Robots always follow predefined motion.
  - No unexpected failures.



Experiments in Simulation

Setup – Routing protocols

- Opportunistic:
  - “Energy Estimate” and “Energy Left”
  - Preferable path 10→9 →…→1 →base
- Schedule-based:
  - CGR and ECGR
  - Contact plan computed *a priori* based on robot motion and cave comm model.
  - Contact between two robots is considered valid if, over a 5 minute interval, the average data rate exceeds 500kbps.
  - Complexity of CGR and ECGR scales with number of contacts. Thus, 5min is computational complexity compromise.



Experiments in Simulation

Setup – Inputs and Metrics

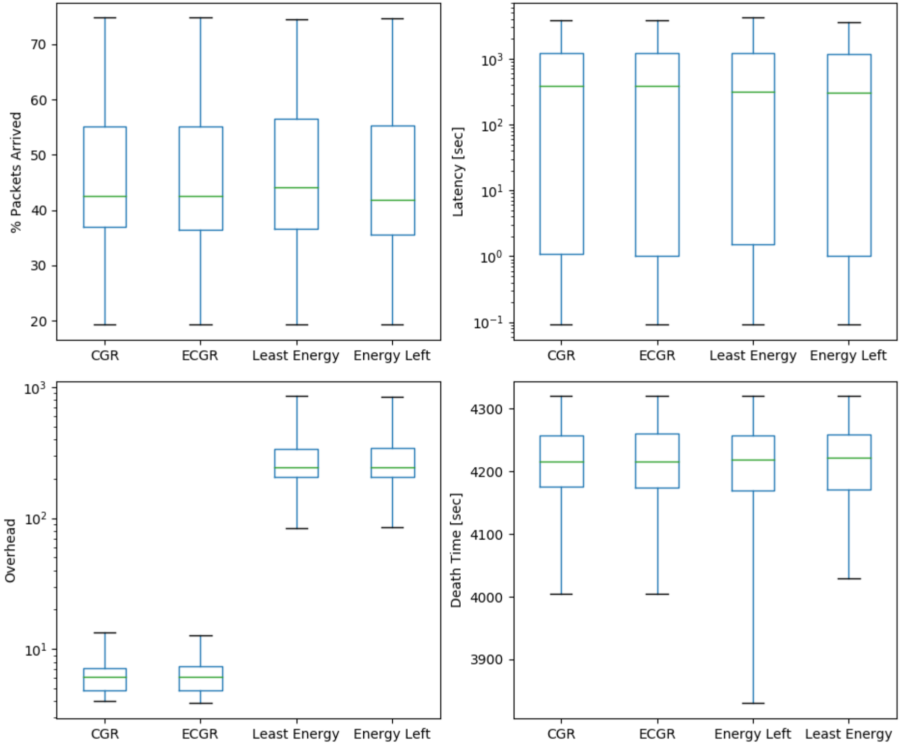
- **Inputs:**
  - Cave dimensions: 100x440m
  - Number of nodes: 10
  - 1Mbit packets generated at a rate of 100kbps, all destined to the base station.
  - Packets have infinite TTL.
  - Simulation lasts until all robots die of battery exhaustion.
  - 20 random observations per routing algorithm.

- **Metrics:**
  - **% of packets** arrived at base station.
  - **Latency** in units of time.
  - **Routing overhead**: # routing calls / packets delivered
  - **Robot death time** due to battery exhaustion.

Experiments

Results

- No significant differences in average packet delivery probability, packet latency and robot death time.
- However, robots deeper in the cave are able to return less data since each hop to a parent robot has a certain failure probability.
- One to two orders of magnitude more routing calls in opportunistic approaches due to inability to pause routing decisions when topology is not varying.
- Results are preliminary (e.g., not clear what are the driving factors in these simulation results).



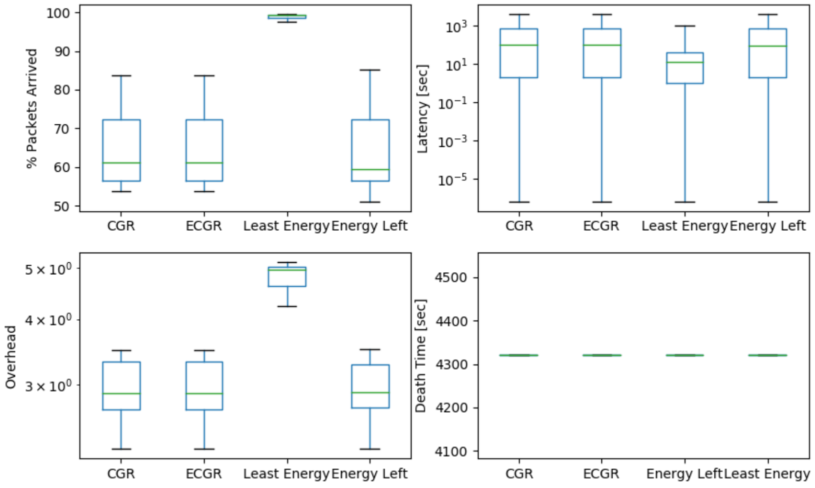
Insights for Future Work

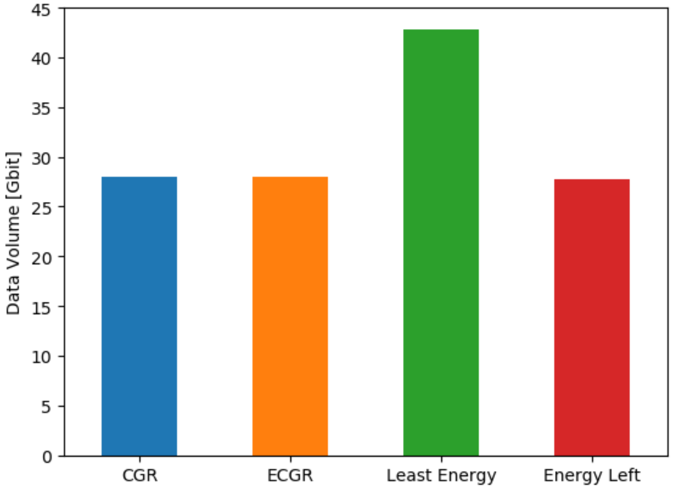
- More tests are needed
- Investigate:
  - Different simulation setup
  - Different configuration and strategies for multi-robot exploration
- Consider other factors:
  - Computational load
  - Comms power variation
  - Heterogenous robots

Extended Results

Max. Data Volume Analysis

- We consider the problem of getting data out of the cave with ON/OFF links. If a link is ON, it always has infinite rate.
- This gives us an upper bound on system performance (i.e. max. data volume that can come out of the cave given the motion and disconnection between nodes).
- We observe that Least Energy router delivers 100% of the data, where the other routers only deliver ~60-70%.
- We also observe that the Last Energy router tends to favor long routes.





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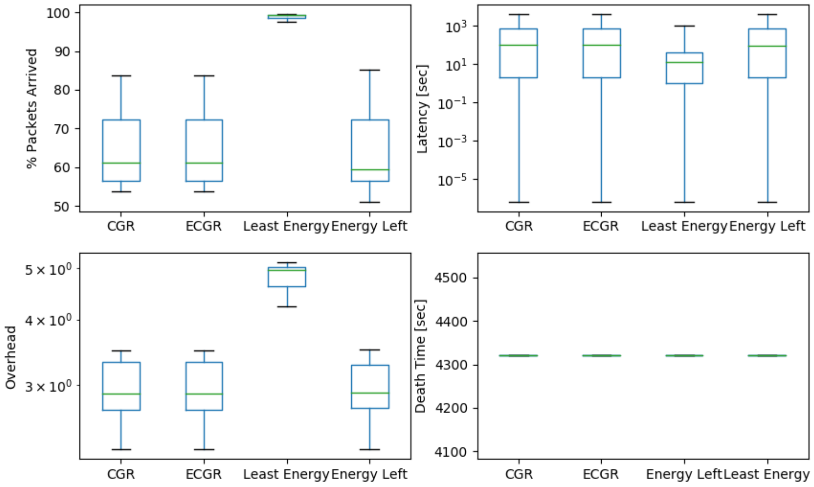
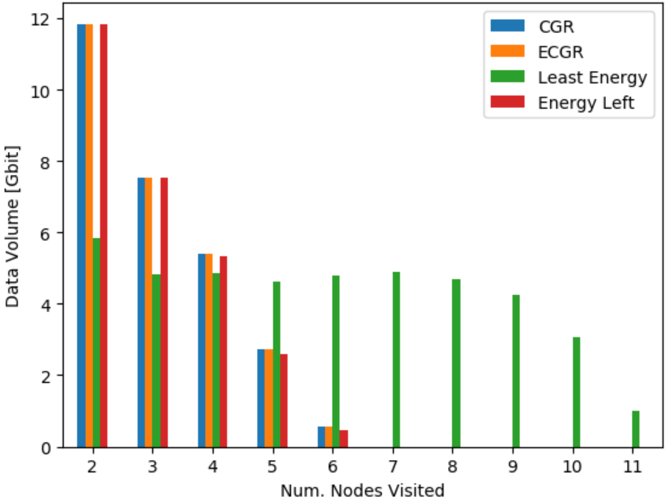
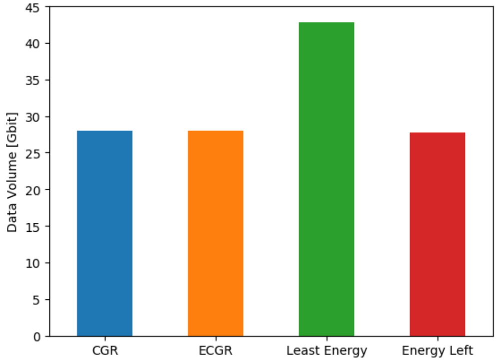
- This gives us an upper bound on system performance (i.e. max. data volume that can come out of the cave given the motion and disconnection between nodes).
- We observe that Least Energy router delivers 100% of the data, where the other routers only deliver ~60-70%.
- This is due to the Least Energy router always choosing long routes (Node i, Node i-1, Node i-2, …, base station).

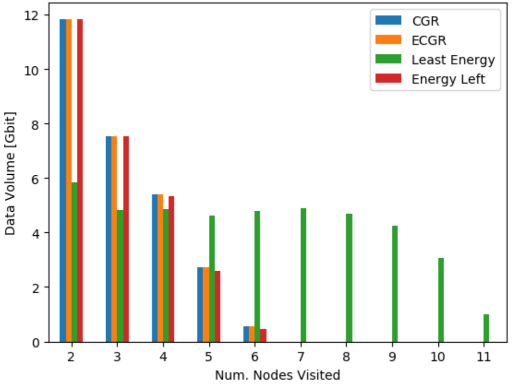


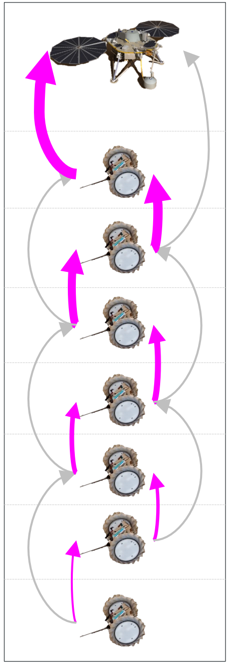


Routing vs. Congestion Level

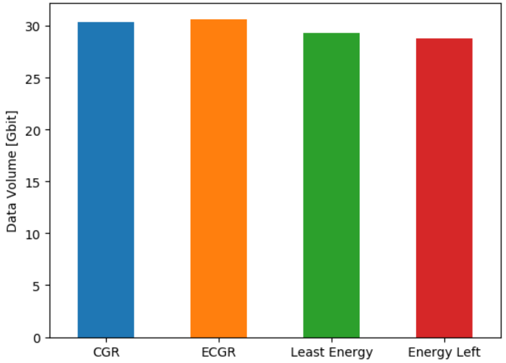
Infinite Bandwidth

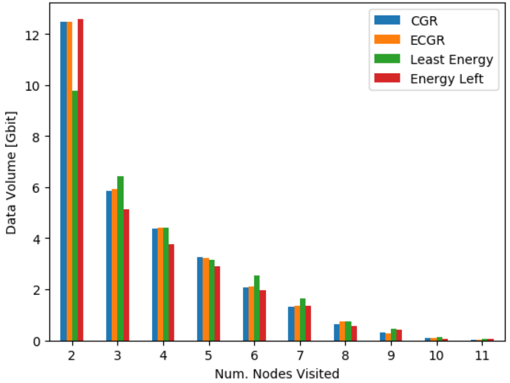


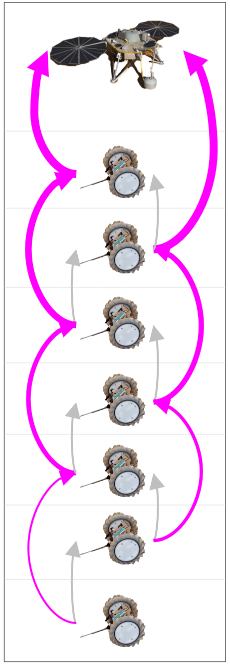




Finite Bandwidth







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Experiments in Simulation

Setup – Cave Exploration Scenarios

- Linear Cave divided in sections
- Sections overlap
- Robot motion precomputed
  - Way-point model
  - Randomized in each sim run
- Cave comm model used
- Robots generate science data
- Assumptions:
  - No recharge
  - Initial battery charge is set
  - Battery decays
  - No unexpected failures
  - Rover follows the predefined plan

Parameter	Value	Units
Cave dimensions	100×440	meters
Num. of nodes	10	-
Node speed	0.05	m/s
Radio type	802.11b	-
Packet size	1	Mbit
Packet generation rate	100	kbps
Packet TTL	∞	sec
Simulation duration	7200	seconds
Hotel power	5	W
Radio power	1	W
Robot battery	21.6	kJ
Num. random observations	20	-